Scientific Revolution: Contested Territory

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THE SCIENTIFIC REVOLUTION: CONTESTED TERRITORY

From 1543 to 1687 some of the giants of science lived, contemplated the natural world, and produced the underpinnings of modern science. Given the accomplishments of the period, it is no wonder that historians have agonized about the idea of an era of scientific revolution. Indeed, the twentieth-century discipline of the history of science began by focusing on the problem of the origin of modern science. The work of some of the discipline's founders concentrated on what this important transformation was and how it came to take place. In recent years, historians have begun to question whether or not such a revolution happened at all. Obviously, the answer depends on how revolution and science are defined: whether there was a gradual transformation of ideas, a gestalt switch, or a sociological innovation. We argue that there was a transformation in the investigation of the natural world, in which new ideas, methods, actors, aims, and ideologies vied with one another for a newly secularized role in the developing nation-states. This, indeed, was a scientific revolution.

The scientific revolution can be understood as a series of overlapping innovations, all important in the creation of modern science. First, natural philosophers took up the epistemological challenges of the ancients and developed a new methodology for uncovering the truth about the natural world. Second, in many different areas, but particularly in physics, astronomy, and mathematics, new theoretical models of the universe were developed. Further, those interested in the investigation of nature formed new institutions and organizations that began to perform the now largely secular tasks of evaluating scientific fact and determining who could be a natural philosopher. Finally, and perhaps most significantly, men interested in the underlying truths of nature developed a new ideology of utility and exploitation, a new structure for scientific practice, and a gentlemanly coterie of scientists who applied their social standards of behaviour to the ideology of modern science.

The New Scientific Method: Francis Bacon and René Descartes

The rediscoveries of ancient natural philosophers and the challenges to that ancient knowledge in the sixteenth century caused scholars in the sixteenth and seventeenth centuries to turn to the epistemological question of how to determine truth from falsity. Perhaps spurred on by the religious turmoil of the sixteenth century, philosophers began to ask the question still fundamental to us today: How can we know what is true? This led to the development of a new form of scientific inquiry—a new "scientific method"—and a new way of articulating this search for certainty. In England this methodology was most fully articulated in the writing of Sir Francis Bacon (1561–1626). Bacon, although not himself a natural philosopher, proposed a reform of natural philosophy in the *Novum Organum* (1620) and *The New Atlantis* (1627). This program of reform was part of a grander scheme to transform all knowledge, especially legal knowledge and moral philosophy. Bacon believed that all human knowledge was flawed because of the Idols that all men carried with them. The Idols were the prejudices and preconceived ideas through which human beings observed the world. Bacon felt that the only way for natural philosophers to disabuse themselves of these Idols was to look at small, discrete bits of nature. The only way to be certain one understood these small bits was to study them in a controlled setting, isolated from the larger (uncontrolled) environment. Using this assumption, he introduced what has come to be called the inductive method. He suggested that increments of information could be gathered by armies of investigators, put together in tabular form, and explained by an elite cadre of interpreters.

Bacon described this in a section of *The New Atlantis* known as "Solomon's House." His methodology, although it appeared to be more democratic than earlier scholastic methods, proposed a means of controlling truth and knowledge by a small elite group who determined what could be studied and what answers were acceptable. In this attitude, he was probably influenced by the fact that he was trained as a lawyer and that he spent much of his political career as an advisor to Elizabeth I and then as Lord Chancellor for James I. He was thus accustomed to the idea of testing evidence in the public venue of a court. As the person most concerned with treason and heresy, he had a distrust of free-thinking and believed that ideas should be controlled by those whose position as custodians of the peace and security of the commonwealth best assured their credibility. One aspect of Bacon's job as Lord Chancellor included overseeing the use of torture in an age when evidence obtained by torture was considered reliable. For Bacon, knowledge was power, and thus an understanding of nature was important precisely because of the practical applications such knowledge would have. In many ways Bacon was a courtly philosopher, so the rhetoric of utility so well employed by Galileo was also present in his work.

This methodology was challenged on the continent by René Descartes (1596–1650) and his followers, who preferred a deductive style based on skepticism. Descartes, like Bacon, came from an influential family and was trained as a lawyer. Unlike Bacon, he worked as a mathematics teacher and practitioner, rather than as a courtier, although in the end the temptation for patronage overcame the struggle involved in living by one's wits. In 1649 Descartes, at the age of 53 the most famous philosopher of his time, accepted the post of Court Philosopher to Queen Christina of Sweden. This was a lucrative post that, like the patronage of the Medicis for Galileo, offered both financial support and status in exchange for glorifying Christina's court and providing philosophical services. Unfortunately for Descartes, whose health was poor, Christina's idea of using his philosophical services was to have him call on her three times a week at five in the morning to instruct her. He was dead of pneumonia before the winter was over. The Swedes sent his body back to France but kept his head. This led to low-grade tension between France and Sweden for close to 200 years, until in 1809 the Swedish chemist Berzelius somehow managed to get Descartes's skull and return it to the French scientist Cuvier, who reunited it with the body.

In *A Discourse on Method* (1637) Descartes offered the first early modern alternative to Aristotle's epistemological system: his method of skepticism. He began by doubting everything, peeling away all layers of knowledge until he came to the one thing he knew was true: that as a thinking, doubting being, he must exist in order to think the doubting thought. He encapsulated this idea in the famous declaration *Cogito ergo sum: I think, therefore I am*. From this starting point he developed through deduction from first principles a series of universal truths that he knew to be self-evident. This deductive method owed its origins to geometric proof, which starts with a small set of sure premises or axioms and proceeds to more complex conditions. Interestingly, although Descartes used this mathematical model and developed new mathematical methodology, most of his scientific theories were explicitly non-mathematical. Also, he was not interested in using experimentation as a means to discover knowledge about nature. Since the senses could be fooled, right reasoning was a much more reliable arbiter in natural philosophical debate than any crude experiment or demonstration might be.

Both Bacon and Descartes attempted to find ways of reasoning that would produce certain knowledge in an age where certainty was giving way to probability. Bacon answered the question of how we can know what is true in a careful, conservative way, involving a hierarchy of knowledge made to appear as a democratic republic of scholars. Descartes answered in an individualistic anti-communal way, which gave more power to individual thinkers but did not, in the final analysis, create a community of scholars.

Mathematics as the Language of Natural Philosophy

One result of this new methodology with its debate about reliable and sure knowledge was the gradual ascendancy of mathematics as the language of natural philosophy. Galileo had been convinced that God created the world in number, measure, and weight, and many other scholars interested in nature echoed this sentiment. For Aristotle, weighing or measuring a substance did not tell you anything interesting about it, but for those investigating nature in the sixteenth and seventeenth centuries knowing how heavy something was or how fast something went was surer knowledge than searching for final causes. They claimed that they only measured and observed rather than imposing underlying hypotheses they sought to prove. Sir Isaac Newton, for example, famously said *Hypotheses non fingo: I feign no hypotheses.* Following Galileo and Newton, natural philosophers increasingly looked for certainty through measurement rather than the analysis of cause.

Significant mathematical developments included the rediscovery of algebra and the development of the calculus; in addition, new and easier notation systems were devised. For example, Descartes instituted the use of *a*, *b*, and *c* for known variables and *x*, *y*, and *z* for unknowns. Mathematicians used these systems as they vied with one another for solutions to increasingly complex algebraic equations.

The creation of analytic geometry, primarily by Descartes but also by François Viète (1540–1603) and Pierre de Fermat (1601–65), placed a powerful tool in the hands of mathematicians and natural philosophers. By combining geometry and algebra, it became possible to transform geometric objects into equations and vice versa. This also opened the door to mathematizing nature, as everything from the trajectory of a cannonball to the shape of a leaf could be turned into a mathematical expression.

In turn, mathematicians began to look for new ways to measure areas under curves and to describe dynamic situations. The result was the invention of the calculus, independently developed by Isaac Newton in England and Gottfried Wilhelm Leibniz (1646–1716) on the continent. The calculus added infinitely small areas together under a curve or described the shape of the curve in formulaic terms. This allowed natural philosophers to accurately describe dynamic situations such as velocity and the motion of acceleration, something not possible with the older geometric and algebraic systems. Some mathematicians were concerned with the philosophical implications of the calculus, since it produced finite answers from the addition of infinite quantities, and the infinitely small and the infinitely large could, paradoxically, be equal. However, in an age that increasingly looked to the practical applications and utility of mathematics, the calculus proved to be an extremely fruitful device and was quickly taken up by the scientific community.

Leibniz was an influential German polymath, trained as a lawyer and employed most of his life by several German princes, especially the three dukes of Hanover. Unfortunately, his relationship with Duke Georg Ludwig (1660–1727) deteriorated, and when Ludwig became King George I of England, Leibniz was forbidden to enter the country. He was very critical of both Descartes's and Newton's work and became embroiled in an acrimonious dispute with Newton over who had invented the calculus first. This dispute, carried on by Leibniz in Germany and Samuel Clarke (1675–1729) in England, was one of the most famous philosophical disputes of the seventeenth and eighteenth centuries, as it ranged over issues of Newtonian natural philosophy and theology. In the end the participants died, and the matter was never resolved. It seems clear now that Newton and Leibniz did develop the calculus independently, with completely different notation and mathematical bases (Newton's was geometrical, while Leibniz's was analytical). In a sense Leibniz won, since the notation that has been used from the eighteenth century to the present is his rather than Newton's.

Mathematical Practitioners

One of the reasons mathematics became such a powerful tool in seventeenth-century natural philosophy was the presence of a new category of scientifically inclined men: the mathematical practitioners. Mathematics had been a quite separate area of investigation, and those interested in its issues had usually tied their studies to practical applications such as artillery, fortification, navigation, and surveying. In the early modern period, these mathematical practitioners provided the necessary impetus in the transformation of nature studies to include measurement, experiment, and utility. Their growing importance was the result of changing economic structures, developing technologies, and new politicized intellectual spaces such as courts, thus relating changes in science to the development of mercantilism and the nation-state. Mathematical practitioners claimed the utility of their knowledge, a rhetorical move that encouraged those seeking such information to regard it as useful.

Mathematical practitioners professed an expertise in a variety of areas. For example, Galileo's early work on physics and the telescope were successful attempts to gain patronage by using mathematics. Descartes advertised his abilities to teach mathematics and physics. Simon Stevin (1548–1620) claimed the status of a mathematical practitioner, including an expertise in navigation and surveying. William Gilbert (1544–1603) argued that his larger philosophical arguments about the magnetic composition of the Earth had practical applications for navigation. Leibniz used his mathematical power to act as an advisor on engineering projects for the dukes of Hanover. As well, many practitioners, including Thomas Hood (fl. 1582–98) and Edward Wright (1558–1615), demonstrated an interest in mapping and navigation.

This new interest in mathematics and in quantifying the behaviour of the world sparked interest in probability. Mathematicians did not believe the world was capricious but that our incomplete knowledge of it limited our comprehension. The introduction of a mathematical evaluation of probability was a step toward understanding complex systems in which not all the determining factors could be known with certainty. Blaise Pascal (1623–62), Pierre de Fermat, and Christiaan Huygens (1629–95) all investigated the mathematical basis of prediction of games of chance, which were popular pastimes in the seventeenth century. Pascal's interest in the geometry of chance had wider implications than gambling at cards and dice, since it led him to develop his probabilistic argument for belief in God, now known as Pascal's Wager. He concluded that, although one cannot know with complete certainty if God exists, by using four possible conditions, one's best probable outcome would result from belief in God. If God did not exist, one lost nothing by believing in Him, but if He did exist, and one believed, one would be saved. Conversely, one lost a great deal by not believing in God if He did exist, while gaining nothing if He didn't exist. (See figure 5.1.)

5.1 PASCAL'S WAGER

	Do Not Believe in God	Do Believe in God
GOD DOES NOT EXIST	Nothing gained or lost	Nothing gained or lost
GOD DOES EXIST	Damnation	Salvation

By the end of the century Jacob Bernoulli (1654–1705) had codified the mathematics of probability, arguing that mathematics gave us the greatest certainty possible in an uncertain world. The concept of probability was not well accepted in physics, however, where Newton's universal laws seemed to provide certain, rather than probabilistic, answers. The shift of the foundation of physics from certainty to probability was one of the most traumatic transitions in modern science, but it would not happen for almost 200 years.

New Models of the Universe

All these new attempts to find a path to certain knowledge were crucial, since natural philosophers were making some radical suggestions about the make-up of the cosmos. The scientific revolution is most clearly identified with the development of a heliocentric model of the universe. This began with Copernicus, who claimed that the Earth revolved around the sun and who developed a mathematical model to explain the movement of the planets. Natural philosophers had been slow to accept Copernicus's theory because it lacked a proper physical justification, such as Aristotle had provided through the concept of natural motion for his cosmological schema. Thus, the so-called Copernican Revolution (historians love to label innovations as revolutions) was incomplete until Sir Isaac Newton (1642–1727), the great English astronomer and mathematician, devised a mathematical model of motion that explained heavenly and earthly movement in a single physical system based on his concept of universal gravitation.

Isaac Newton: The Great Polymath

Isaac Newton was born on Christmas Day, 1642, coincidentally the same year that Galileo died. His father died before he was born, and his early life was not happy, spent in conflict with a stepfather he disliked and a mother who expected him to

CONNECTIONS

Science and the Marketplace: Mathematics for Sale

During the sixteenth century, many mathematical practitioners made their living by giving lectures and instruction, selling instruments, and performing a variety of mathematically based activities such as surveying or casting horoscopes. The booming metropolis of London provided an excellent marketplace for these skilled men, whose work demonstrated the interconnection of natural philosophy, mathematics, and the mercantile society of the time.

The first mathematical practitioner in London was Robert Recorde (1510–88). Trained at Oxford, he was largely responsible for introducing arithmetic and mathematics to a wider audience in England and for re-establishing a mathematical language and discipline into English scholarship. Recorde wrote a number of foundational books on mathematics in English. He was commissioned by the Muscovy Company (a merchant company that traded in northern Europe and was seeking the Northeast Passage to Cathay) to give lectures and to write a series of books on geometry, spherical geometry, astronomy, and navigation for use by their navigators. At the same time, he introduced Euclidian mathematics and algebra to an English audience, allowing natural philosophers to use mathematics in ways they had not done before.

Recorde was soon followed by other mathematical lecturers in London, sponsored by guilds, companies, or the City of London itself. Thomas Hood (1556?–1620), for example, was the first mathematics

run the family farm. Newton had no aptitude for farming, and his mother despaired of finding him a livelihood. Fortunately, the local vicar noticed his scholarly potential and helped procure him a scholarship to Trinity College, Cambridge. Newton was a relatively undistinguished scholar, except for mathematics; he taught himself geometry from Descartes's works and algebra from Viète's. In due course, he was made a Fellow of Trinity College in 1664 and was appointed Lucasian Professor of Mathematics in 1669. The latter was a prestigious position, although he often lectured to empty rooms. His teacher, Isaac Barrow (1630–77), had to pull strings in order to get him this position, since Newton did not believe in the special divinity of Christ or in the Trinity. This made him a potential heretic, since he would not take the required oath of uniformity to the Church of England, which was normally required for any high academic or government position.

lecturer paid by the City of London. In 1588, Hood petitioned William Cecil, Lord Burghley, to support a mathematics lectureship in London, to educate the "Capitanes of the trained bandes in the Citie of London."* Hood identified himself on the title pages of all his books until 1596 as Mathematical Lecturer to the City of London, sometimes advising interested readers to come to his house in Abchurch Lane for further instruction, or to buy his instruments. His books explained the use of mathematical instruments such as globes, the cross staff, and the sector, suggesting that his lectures and personal instruction would have emphasized this sort of instrumental mathematical knowledge and understanding. He was also known to have cast horoscopes, another way to make money.

Those who gave and attended these mathematical lectures had some expectation that they would be able to buy, sell, and use the instruments that were being discussed there. It is no surprise, therefore, that just as these lectures were being presented to the London community, mathematical instrument makers were beginning to ply their trade in increasing numbers in late-sixteenth-century London. Thomas Gemini, a goldsmith, was probably the first English instrument maker starting in the 1550s, followed by Humphry Cole in the 1580s. After that, many men set up shop and sold navigational instruments, surveying instruments, maps, globes, and astrolabes, as well as providing the informal instruction for those who were interested in using them.

By 1610, there was a strong practical mathematical community living in London. A number of mathematical lectures had been sponsored, attended by a variety of audiences. Books and individual lessons explaining the use of mathematics and mathematical instruments had been produced, all leading to an increasing number of men trained in and sensitive to mathematical tools and explanations. A variety of men met in the instrument shops and at the mathematical lectures—gentlemen, scholars, merchants, and navigators. Mathematics was becoming both a language of commerce and of natural philosophy.

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* British Library manuscript, Landsdowne 101, f. 56.

While Newton would not compromise his religious beliefs, he kept his views very private for his entire life.

In 1665 the Great Plague returned to England. It swept through Cambridge, and Newton was forced to return to his mother's home. The enforced isolation allowed him the opportunity to put together a number of ideas he had been developing through intensive reading during the past four years. Although it is unlikely that an apple really fell on his head, during the following year, his *annus mirabilis* (miraculous year), he worked out theories about gravitation, physics, and astronomy. As if that were not enough, he also created the calculus and began his investigations into optics and theories of light.

Although Newton studied planetary motion during that year, he did not publish his results until 22 years later. He was dissatisfied with his mathematical results to the question of why the orbits of the planets were circular, or nearly circular, and so put them away for a time in order to concentrate on alchemy and theology, including his long-standing interest in the books of Revelation and Daniel. He spent many hours over the next 13 years reading commentaries on scripture, studying the Bible, and constructing his personal theology. This theology was complex, most closely resembling an extreme form of Unitarianism or Arianism, which argued that Christ was not divine but the highest of God's created beings. Over his lifetime, Newton spent more time studying theology than any other subject.

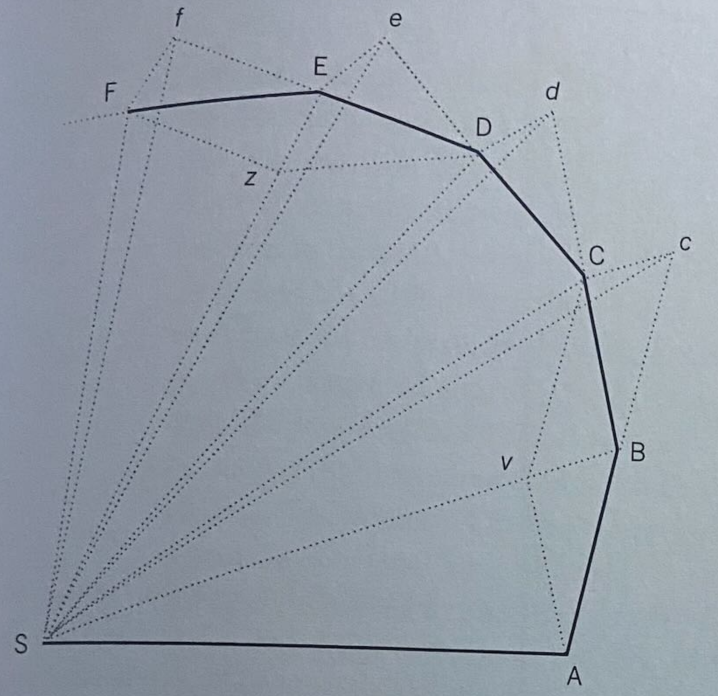
In 1679 Robert Hooke (1635–1703), Corresponding Secretary of the Royal Society of London, wrote to Newton to find out what he was doing. It was Hooke's job to act as a kind of intellectual pen pal, communicating with members of the Royal Society and putting people with similar interests in touch. Newton and Hooke had a strained relationship, however, since Hooke had criticized Newton's earlier optical work. What, Hooke asked in 1679, would be the path of a body (a rock, for example) released from a high tower down to a rotating earth? Newton replied that he was not presently engaged in natural philosophical investigations, but he suggested that it would spiral east to the centre of the earth because the angular velocity from the top of the tower was greater than on the earth's surface. Hooke argued that this was not so: the path would be the result of a horizontal linear motion at constant speed combined with an attractive force toward the centre and varied inversely with the square of the distance between the body and the earth. This caused Newton to wonder whether his original question in 1666 as to why planetary orbits were circular was misdirected.

Newton set to work on mathematical models of elliptical orbits. In 1684 his friend Edmund Halley (c. 1656–1743, and the discoverer of the comet that bears his name) rode out to Cambridge to try to get Newton to communicate some of his mathematical work to the Royal Society, a difficult task since Newton was very secretive and refused to publish anything. Halley said that he and his friends, the architect and natural philosopher Christopher Wren (1632–1723) and Hooke, had wondered what motion an orbiting body would traverse if attracted to a central body by a force that varied inversely as the square of the distance between them. Newton replied that in 1679 he had proven to his own satisfaction that it would be an ellipse, although he did not have the demonstration available. Halley was deeply impressed, seeing this as a breakthrough in mathematical astronomy, and urged Newton to publish. He even promised to finance the publication. Newton agreed and in an astonishingly short period produced the book that changed astronomy and physics. Published in 1687, *Philosophiae Naturalis Principia Mathematica* (*The Mathematical Principles of Natural Philosophy*, usually known simply as the *Principia*) laid out Newton's theory of universal gravitation and established a mathematical and mechanical model for the motion of the whole universe. In this work he used the mathematical models of Galilean physics and combined them with the planetary models of Copernicus and Kepler.

Newton had produced a universal physics, a Grand Synthesis, which finally allowed astronomers to move away from Aristotle with confidence. He had produced a real model of the universe rather than merely a mathematical set of calculations, such as Copernicus had put forward.

In the *Principia* Newton defined force for the first time, adding it to matter and motion as the third essential quality of the universe. Force, he said, was necessary to compel a change of motion. Without force, a mass (another term he originated) would continue at rest or in rectilinear motion, due to inertia. This is often called Newton's First Law. His Second Law showed the way to measure force mathematically, now expressed as $f = ma$, and his Third Law asserted that for every action there is an equal and opposite reaction. In order to understand the motion of the bodies in the universe, Newton insisted that they operate in absolute time and space. In the Newtonian system, absolute time and space were independent and unchanging aspects of reality. Absolute time was uniform, progressing at the same rate of change, everywhere in the universe and at all past and future moments. People could not perceive absolute time directly, but could infer it mathematically by observing the motion of the planets and stars. Absolute space was the unmoving and constant dimension of the universe. This meant that all observers saw the motion of the stars and planets (and everything else) within absolute space, and thus they should all see the same motion as measured against the unchanging dimension of absolute space. The implications of this were profound. It meant that Newtonian physics was truly universal and someone measuring the universe from a distant star would get the same results as we would.

Newton took the concept of centrifugal force (the tendency of an object to fly away from a circular path) and stood it on its head. In his early work in 1666, he had followed the older view of circular motion, which sought to quantify and explain this tendency to fly away. But, in a major insight, the *Principia* argued for a centripetal force instead, a force that pulls objects into the centre. This is gravity. Thus, the moon's motion is composed of two parts: first, inertial motion carries it in a straight line; second, gravity constantly forces it to fall toward the Earth. The balance of these two forces holds the moon in orbit. (See figure 5.2.)



5.2 NEWTON EXPLAINS THE MOON'S MOTION

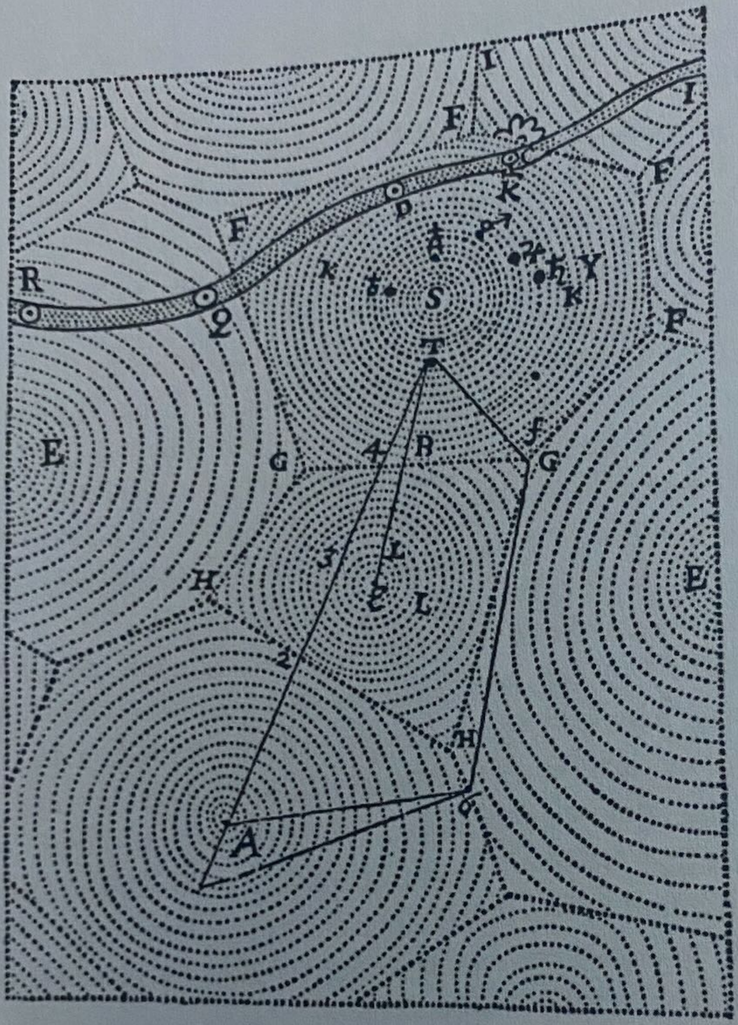
From Newton, *Principia Mathematica*, Proposition I. At each point, A, B, C, etc., the moon's motion seeks to move in a rectilinear line away from S, but is drawn back by centripetal force (gravity) toward S.

Newton set up his argument in order to disprove Descartes's theory of vortices, which Descartes had articulated in *Principia Philosophiae* (1644). Descartes had argued that the universe was like a machine, a concept called "the Mechanical Philosophy." Except for those parts filled with coarse matter (such as the Earth), the universe was a plenum, or a space filled with an element called ether. The planets moved in a sort of whirlpool of ether that carried them along in their orbits. (See figure 5.3.)

The *Principia* was in many ways an attack on Descartes's book (the title reflected Descartes's), which is why Book Two concentrated on the study of how fluids work and how things move through them. This exploration of fluid mechanics may confuse modern readers, since it seems to have little to do with forces, gravity, or the motion of the planets. Newton's objective was not just to present his own system but to discredit Descartes's by showing that the vortex model was critically flawed.

The most far-reaching and long-lasting achievement of the *Principia* was how Newton found a way to tie together through the concept of universal gravitation the orbits of the planets and the satellites (including the moon and comets), Galileo's law of falling bodies, the fixation of objects to the Earth, and the tides. He proved that an apple falling from a tree obeyed the same laws as the moon orbiting the Earth. He had a law that applied to *everything*—the moon, the satellites of Jupiter and Saturn, the Earth, rocks, and the distant stars.

The sheer power of Newton's universal laws suggested to scholars in many different fields that there should be similar laws governing human interaction as well. Philosophers from many other areas, including economics and political philosophy, searched throughout the eighteenth century for such laws and argued that any society that failed to follow the universal laws was doomed to failure.



5.3 DESCARTES'S VORTEX COSMOLOGY

Points S, E, A, and are centres of vortices. By the churning of the corpuscles within each vortex, the centre is self-illuminating, and thus is a star. Around S (the sun) move the planets, swept along by the vortex (T is the earth or terra). The stripe at the top indicates a comet's path. From Descartes's *The World or a Treatise on Light* (1664).

Ironically, the *Principia* was not a popular or financial success. The Royal Society, the pre-eminent institutional home of English science, refused to sponsor it, since their previous publishing venture, Francis Willoughby's *History of Fishes*, had been a financial disaster. They were unable to sell more than a handful of copies of this expensive illustrated book and were forced to give it to their employees, especially Robert Hooke, in lieu of salary! The members of the Royal Society, perhaps accurately, saw the *Principia* as a book with a limited readership and so forced Halley to fund it himself, which he did through the sale of subscriptions. This story reminds us that, as revolutionary as we might now consider Newton's work, at the time it held the interest of a limited audience because so few people could understand his mathematical arguments.

Newton and Alchemy

Because Newton considered his studies esoteric, accessible only to a select few, he was not overly concerned about reaching a wide audience. One aspect of his work that has been overshadowed by his physics and mathematics and so has faded from modern consciousness was his great interest in alchemy. Both Newton and Robert Boyle were involved in alchemical investigations, looking both for the Philosopher's Stone and the basic structure and functioning of nature. Although "multipliers," or alchemists interested only in gold, were looked upon as crass, many respectable gentlemen studied alchemy. Both Newton's and Boyle's investigations came from the belief in God's ordering of the universe and were a search for the active principles that animated nature, another attack on mechanical philosophy. Since Newton was interested in how the universe worked on a microscopic as well as a macroscopic level, he investigated what the prime matter of the universe was. He read both ancient and modern authors copiously and performed experiments of long duration. Because of his expertise in this area, in later years he was appointed Master of the Mint, in which position he assessed those who claimed to have produced gold. At his death, a number of people interested in alchemy were anxious to gain access to his extensive library of alchemical works.

In spite of his lack of bestseller status and his more arcane studies, Newton was the most famous scientist of his generation. He received many important marks of honour indicative of his high status, including his position as Warden and then Master of the Mint and election as President of the Royal Society. His opulent state funeral in 1727 demonstrated his exalted position, and reports of the event were transmitted around Europe, with Voltaire (who was deeply influenced by Newton's natural philosophy) providing one of the eye-witness accounts. Voltaire was extremely impressed that a natural philosopher, and one with heterodox religious views at that, was buried with such pomp and circumstance. Here was a country that understood the importance of its intellectuals!

Mechanical Philosophy

At the same time that Newton was introducing a mathematical basis for motion throughout the universe, other natural philosophers were searching for a more concrete model. Some, looking to the new instruments and machines being developed around them, argued that the world itself was a sort of machine. As men constructed more and more precision mathematical instruments, especially for navigation, astronomy, surveying, and timekeeping, and more complex machines, this suggested to them that God might have created the most complex machine of all. This conception of the world operating in a mechanical fashion became known as the Mechanical Philosophy or, alternatively, the atomical or corpuscular philosophy. It was first developed by René Descartes and Pierre Gassendi (1592–1655). Descartes especially extended the mechanical philosophy to include living things, arguing in his *Treatise on Man* (1662) that human physiology operated just like a machine. Corpuscular philosophy was later taken up by the Englishmen Robert Boyle and Thomas Hobbes, the latter of whom used it in his political theories. Basically, it was an interpretation of the world as a machine, either as a clock (implying order) or an engine (showing the power of nature). If the universe was a machine, then God was the Great Engineer, or Clockmaker. At first, Gassendi devised this interpretation of nature to give God a role as a transcendent, rather than immanent, being. That is, Gassendi argued that God could exist outside the material universe because He had set a mechanical structure in place. There was no need for God to exist within and tinker with an imperfect world. Corpuscular philosophy was eventually accused of being atheistic because, if the universe were a perfect clock, it would never stop, and there would be no need for God. The claim that natural philosophers were removing God from the universe was unfair but widespread, affecting Newton as well as Gassendi. It recurred in many forms and as a charge against many philosophers and scientists over the next centuries.

Mechanical philosophy was rooted in ancient theories of atomism, held by Epicurus, Democritus, and Lucretius, which had been rediscovered by the humanists. These ancient thinkers had posited that the world was composed of infinitely small simple particles. For the ancient Greeks, this had shown the eternity and total materiality of the world, an aspect of the theory that Descartes and especially Gassendi (a Catholic priest) set out to change. They argued that although it appeared that the world had existed forever, this could not be true, which meant that its creation was of a different kind than its operation and was, therefore, known by God, but unknowable through natural philosophy. A material universe could not be used as a proof for or against the existence of God, since God's existence was a metaphysical, not physical, question.

Mechanical philosophers reduced matter to its simplest parts, atoms, just as Descartes had stripped away ideas through skepticism. These atoms had only two qualities: extension and motion. Since extension was a definition of matter—that is, that matter must take up space and all space must be matter—a vacuum was not possible in this philosophy. Therefore, the universe was filled with a plenum of particles. All force-at-a-distance was actually motion through the plenum, which explained magnetism and the motion of the planets. It was this aspect of Descartes's theory that Newton had attacked so forcefully in the *Principia*. And the question of whether or not a vacuum could exist in nature was soon taken up in Robert Boyle's experimental program. It is a great historical irony that the close examination of the nature of matter, meant to prove mechanical philosophy, refuted the very theory that the universe was full of matter.

The Use of Experiments as Proof: William Harvey and Robert Boyle

Experimentation, as a source of sure knowledge about nature, was new to the early modern period. Aristotle, of course, had argued that forcing nature into unnatural situations would tell us nothing about how it really behaved. This attitude began to change in the sixteenth century, partly because of new attitudes toward certainty and man's power over nature, and partly because skilled instrument makers were able to create precise philosophical instruments. Francis Bacon, who as Lord Chancellor had overseen the torturing of traitors, believed that human beings, when subjected to extreme pain, would be forced to tell the truth. Likewise, putting nature on trial, including torturing nature through experiments, would force her to reveal her secrets. While the reliability of truth claims as a result of experimentation was under constant scrutiny in this period, it is fair to say that one of the significant changes to the study of nature in this period of scientific revolution was the increased use of, and reliance on, experimentation.

Probably the first extended discussion of experimentation came from the study of human anatomy in the work of William Harvey (1578–1657). Following the success of Vesalius in the sixteenth century, scholars developed a keen interest in the structure and function of living things. For example, Girolamo Fabrici (c. 1533–1619) examined the structure of veins and in 1603 found the existence of valves at particular intervals. Harvey, using keen observation, some well-thought-out experiments, and a belief in the similar structure of all animals including humans (what was later called comparative anatomy), developed a theory of the circulation of the blood that proved very influential in the years that followed.

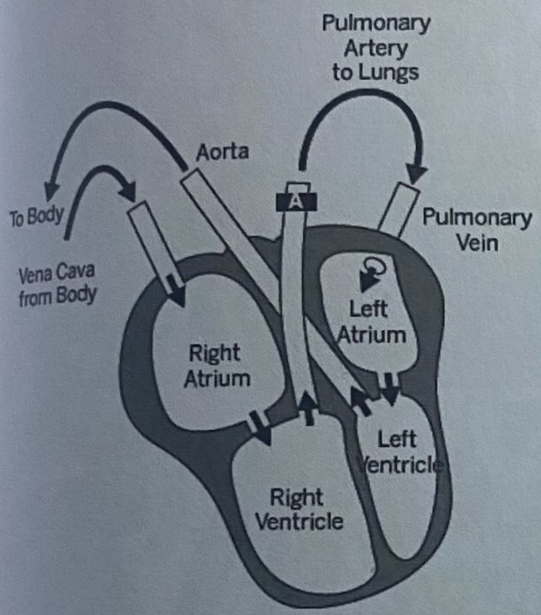
Harvey received his medical training at Padua, where Vesalius had taught, and returned to London in 1602 to work first as a physician at St. Bartholomew's

Hospital and eventually as Royal Physician to Charles I. While in these positions he conducted a series of experiments on the blood in animals. This resulted in the publication of *On the Movement of the Heart and Blood in Animals* (1628), in which he demonstrated that the blood in animals and humans was pumped out by the heart, circulated through the entire body, and returned to the heart. He proved this through a series of elegant experimental demonstrations, some involving vivisection of animals and some less invasive demonstrations with humans. In his preface Harvey drew the political parallel between this circulation and the movement of citizens around their king, indicating his close affiliation with the Royalist side of the civil war soon to erupt in England.

One of the clearest experiments that Harvey performed was his proof that there were no passages through the septum of the heart. From Greek times through Galen and Vesalius, anatomists had argued that blood must pass through the wall separating the two ventricles or large chambers of the heart. While this explanation satisfied some aspects of the assumed purpose and path of blood, problems persisted. The first was the question of volume, since the old system required the liver to produce a constant supply of blood that was completely consumed by the rest of the body. This seemed to Harvey to be out of all proportion to the amount of matter that went into the body. The second problem was purely anatomical. While Galen had said there were pores in the septum, Vesalius, who worked with human hearts rather than the cow and pig hearts that Galen had used, could find no such passages. Rather than contradict Galen completely, Vesalius argued for a permeable septum with either sponge-like tissue or pores too small to see.

Harvey reasoned that if blood were circulated, a far smaller volume would be needed; it was simpler to conceive of a re-used supply of blood than a constantly created and consumed supply. At the centre of the system was the heart, working as a pump, but to demonstrate the two-part circulation (heart-to-lungs and back, heart-to-body and back) he had to show that blood did not move from the venous to the arterial system by way of the chambers of the heart. In a later experiment he demonstrated this, using a cow heart and a bladder of water. He tied off the passages to the heart so that he could squeeze water into one ventricle and see if it passed into the other. When it did not, he had the first proof that the blood did not pass through the septum. He then tied or untied the constraints and used the bladder of water to show that the blood must pass in sequence from right atrium to right ventricle and out to the lungs, and then through the pulmonary vein to the left atrium and left ventricle and out to the body through the aorta. While it was still unclear how the blood got from the arteries through the tissues of the body and back into the veins (and would remain unclear until microscopy developed far enough to see the microvessels at cell level), Harvey's work better explained the evidence than the older system. (See figure 5.4.)

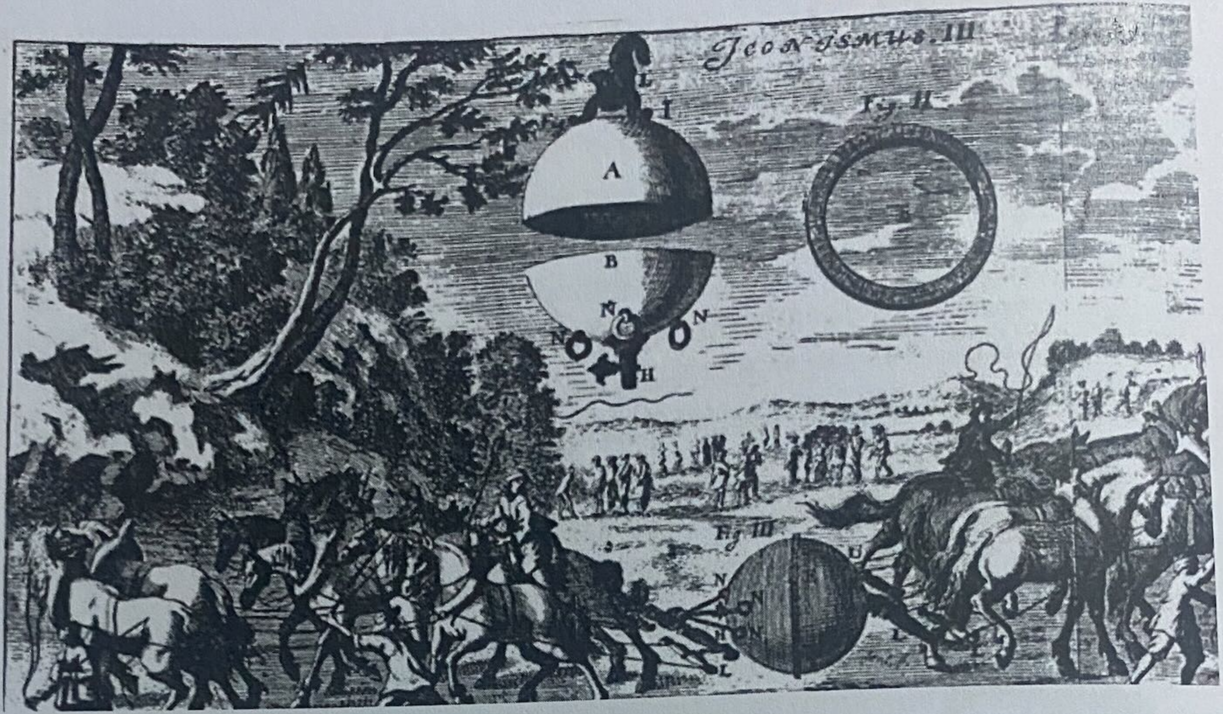
Harvey also used careful observation and some experimentation in his embryological studies. Fabrici, in his book *On the Formation of the Egg and the Chick* (1621), had observed that in viviparous generation the embryo was created by a union of semen and blood from the parents. Harvey followed this work with a close examination of the development of ova. He examined fertilized eggs from their unformed state to birth, tracing even more closely the stages of growth. He published this work in *Exercises Concerning the Generation of Animals* (1657). This spurred further work by Marcello Malpighi (1628–94), who introduced the use of microscopic observations of ova development in 1672.



5.4 HARVEY'S MODEL OF THE HEART
Harvey closed off the artery at "A" and pumped water through the vena cava to demonstrate that no fluid passed from the right ventricle to the left ventricle.

The work of Harvey and Malpighi, showing the power of observation and experiments, accorded with the inclination among many natural philosophers to use instruments and demonstrations to isolate phenomena and break down investigations into smaller components. Perhaps the man most responsible for the elevation of instrumental investigation during the scientific revolution was Robert Boyle (1627–91). Boyle, the son of an Irish noble family, came to Cambridge during the English Civil War and became a key player in the creation of the Royal Society after it. He joined the elite of London society from the 1660s onwards, living with his sister, Lady Ranelagh, in her house in Pall Mall, and entertaining royal and scholarly guests alike at his laboratory there. While at Cambridge, he set up his own alchemical laboratory to investigate the underlying make-up of matter. He denounced old-fashioned alchemical investigations and, in *The Skeptical Chymist* (1661), laid a foundation for the new study of chemistry.

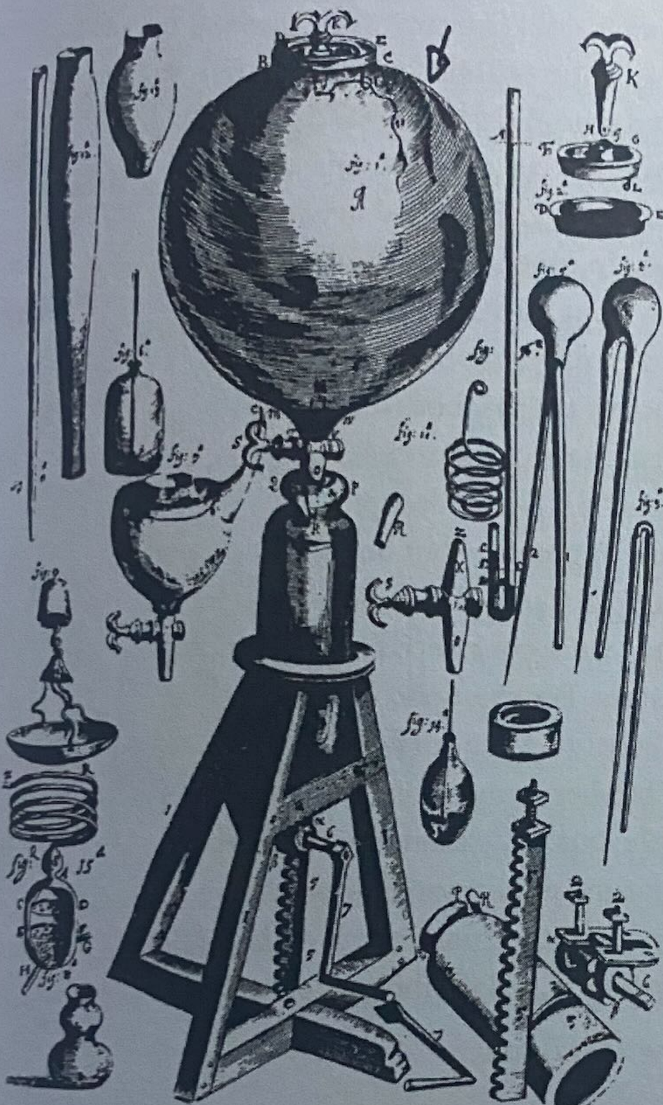
Boyle, with Robert Hooke as his assistant, investigated airs, using a newly devised air pump. He employed instrument makers to attach a large, carefully blown glass globe to a pump in order to evacuate the air from the globe. In this, he



5.5 ILLUSTRATION OF VON GUERICKE'S MAGDEBURG EXPERIMENT

followed the lead of Otto von Guericke (1602–86), who had performed his own air experiments in the 1640s. Most famously, in 1657, von Guericke demonstrated that two teams of horses hitched to joined hemispheres of copper (the so-called Magdeburg hemispheres) from which the air had been evacuated could not pull them apart, since the weight of the air outside the spheres was so much greater than that on the inside. (See figure 5.5.)

Boyle and Hooke built their first air pump in 1658 and performed a number of experiments. (See figure 5.6.)They demonstrated that air had weight, that a vacuum could exist, and that some component of air was necessary for respiration and combustion. Their results were published in 1660 as *New Experiments Physico-Mechanical Touching the Spring of the Air and Its Effects*. Boyle used his air pump for less spectacular demonstrations than von Guericke, for example, placing small animals in the glass sphere, removing the air, and watching them perish, or alternately placing candles therein and watching the flame extinguish. (See plate 4 for a later depiction of these events.) From these experiments he concluded that there was something in the air that supported both life and combustion. His work was thus connected to Harvey's because it touched on what part of air was needed for life and that it seemed to be brought into the body by way of the lungs. This was part of a growing interest in "vitalism," the search for the spark of life that transformed inanimate matter into living plants and animals.



5.6 BOYLE'S AIR PUMP AND TOOLS FROM *NEW EXPERIMENTS PHYSICO-MECHANICALL* (1660)

Boyle's work also demonstrated the relationship between pressure (the "spring" of the title) and volume of air. He and Hooke used a j-shaped tube filled with mercury to show that increasing or decreasing the pressure on the short stem raised or lowered the level of mercury in the long stem. (See figure 5.6.) Boyle argued that "according to the *Hypothesis*, that supposes the pressures and expansions to be in reciprocal proportion";[1] in other words, as pressure goes up, the volume of air goes down in equal proportion and vice versa. While Boyle was making a specific argument about atmospheric air, which he considered an elastic fluid, not an element in itself, the basic relationship he pointed out was later transformed into $PV = K$, what we now call "Boyle's Law" or occasionally "Mariotte's Law" after Edmé Mariotte (1620–84) who independently found the same relationship in 1676.

Unfortunately, Boyle's air pump was plagued with problems. It leaked quite badly, so that it was not really possible to evacuate all the air from the interior. Also, although he published detailed accounts of his instrument and its operation, complete with schematic diagrams, other natural philosophers across Europe could not replicate his results. Thomas Hobbes (1588–1679), a natural philosopher as well as a moralist, severely criticized the work of Boyle and Hooke. Hobbes claimed that the air pump did not work and that it in no way represented a vacuum, as they had claimed. Although Hobbes presented many sound arguments, Boyle's rising status, both socially and scientifically, ensured that his was the winning side of this disagreement.

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[1] Robert Boyle, *A Defence of the Doctrine Touching the Spring and Weight of the Air* (London: M. Flescher, 1682) 58.

Despite equipment problems, the claim of replicability became fundamental to the experimental program from Boyle on. That is, natural philosophers began to claim that experiments were useful and produced true and certain results precisely because they were not dependent on the experimenter but could be repeated by anyone. The air pump was to be seen as transparent; nothing stood between the observer and the aspect of nature being observed. In other words, an ideology of the objectivity of instrumental experiment arose from Boyle's work with the air pump. Our modern reliance on experimentation—and on replicability—is in part based on the triumph of Boyle and the Royal Society over Hobbes and other skeptics. That "proof" (that is, evidence of the true state of nature) results from experimentation was, and is, a powerful idea, even if it has philosophical flaws. Many things make an unmediated view of nature impossible, but because of Boyle's status and the status of his witnesses, the air pump became "black-boxed." That is, the air pump and other experimental instruments were considered neutral and objective, unproblematically revealing nature's state. For example, when we look at a thermometer to help us decide what kind of coat to wear outside, we have accepted a particular concept of temperature. The thermometer is not an unbiased object but embodies a philosophical idea about the quantification of nature. To someone unfamiliar with the concept of temperature, a thermometer would be a meaningless device. This does not mean that what the thermometer reveals is false but that all scientific instruments represent a system of beliefs about the world.

The Development of Philosophical Instruments

During the seventeenth century, other instruments (often called philosophical instruments) and experimental programs were devised, all sharing this ideological stand with Boyle's work. Boyle himself used the barometer, developed in 1644 by Evangelista Torricelli (1608–47), and others followed this lead in investigating the weight of air. Torricelli filled different glass tubes with quicksilver (mercury), inverted them into a basin, and discovered that all the tubes maintained a constant level. Torricelli claimed that the space above the mercury, the "Torricellian space" as Boyle called it, was a vacuum and argued that "we live submerged at the bottom of an ocean of the element air, which by unquestioned experiments is known to have weight."[2]

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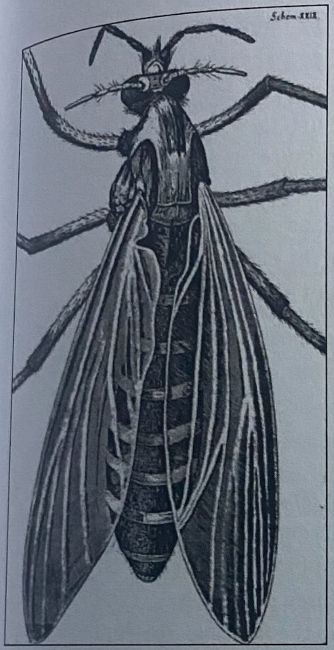
[2] Evangelista Torricelli, "Letter to Michelangelo Ricci" (1644), in *Encyclopedia of the Scientific Revolution*, ed. Wilbur Applebaum (New York: Garland, 2000) 647.



5.7 ILLUSTRATION FROM ROBERT HOOKE'S *MICROGRAPHIA* (1665)

He also predicted that if one ascended to higher altitudes, the weight of air would be less and the column of mercury would descend further. This prediction was taken up by the mathematician Blaise Pascal. Pascal first worked to replicate Torricelli's instrumental experiment, which proved a difficult task. He eventually succeeded, both with a column of mercury and with a much larger one of water. This resulted in a heated debate about the possibility of a vacuum, strongly denied by a number of leading theologians. To avoid this discussion and concentrate instead on the question of the weight of air, in 1648 Pascal took the barometer up a mountain near his brother-in-law's home in Clermont, France. Sure enough, the higher the ascent, the lower the column of mercury and the larger the "Torricellian space" at the top of the tube. Because Pascal soon thereafter had a crisis of faith and turned from natural philosophy to spirituality, the results of this investigation were not known until after his death, with the posthumously published *Traités de l'équilibre des liqueurs et de la pesanteur de la masse de l'air* (1663). This work, with Boyle's, set up an experimental research program for the coming century, as well as demonstrating the power and "objectivity" of philosophical instruments.

Perhaps the most innovative philosophical instrument of the seventeenth century was the microscope, first developed in the first decade of the century. Following the success of the telescope to bring distant sights closer, unknown instrument makers, probably in the Netherlands, produced instruments designed to greatly magnify the very small. The five microscopists best known for their startling observations and discoveries were van Leeuwenhoek, Hooke, Malpighi, Swammerdam, and Grew. Antoni van Leeuwenhoek (1632–1723), a merchant in Delft, first turned these magnifying devices on a variety of substances, most famously male semen, where he claimed to observe small animalcules in motion. This resulted in a series of interesting letters to the Royal Society. Robert Hooke turned to the favourite subjects of microscopists—insects, seeds, and plants—and captured some stunning images of various enlarged phenomena through engravings in his bestselling, lavishly illustrated book, *Micrographia* (1665). (See figure 5.7.)

The Italian anatomist Malpighi turned the microscope on the human body and, in addition to his embryological work, discovered capillaries and their role in the circulation of the blood. Jan Swammerdam of Amsterdam (1637–80) disproved contemporary theories about the metamorphosis of insects, while the Englishman Nehemiah Grew (1641–1712) found the cellular structure of plants. All five successfully overcame early suspicions that the instrument was creating and disguising as much as it was revealing to produce theories and observations much sought after by the natural philosophical community. By the eighteenth century the vanishingly small was seen to be observable, without scientists worrying about any interference from the apparatus itself.

Newton and the Experimental Method

Isaac Newton also played a part in the development of experiment (and experimental instruments) as a legitimate methodology. Beginning during his *annus mirabilis* he developed a theory of light based on a series of simple and elegant experiments. Because of a decades-long dispute with Hooke about optics, he refused to publish, but in 1703 Hooke died. Newton's *Opticks* came out in 1704. Unlike the *Principia*, the *Opticks* was written in English, in simple language, and laid out so that the experiments could be recreated by anyone who could read the book and afford a few pieces of optical equipment such as prisms, mirrors, and lenses. Even more than Harvey or Boyle, who had likewise explained their procedures in print, Newton became the model for the new experimental method. It was a smash hit, snapped up by an eager public and translated into French, German, and Italian within the year. It has been in print almost continuously to the present day.

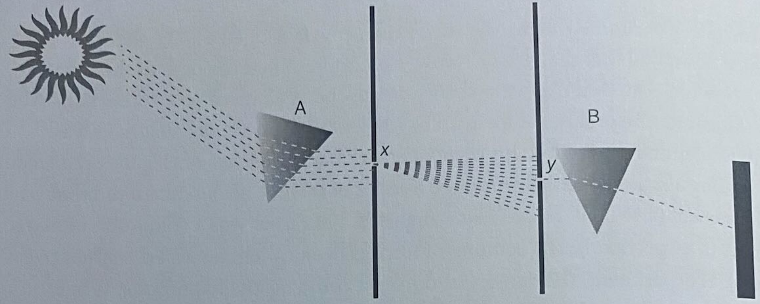
Newton was contributing to a long tradition of optics research, stretching back to the Middle Ages and earlier Arabic natural philosophers. He was also building on the work of Kepler, who had argued that light travelled in rectilinear rays, enabling a mathematical description of its path. This allowed several natural philosophers, including Thomas Harriot (c. 1560–1621), René Descartes, and Willebrord Snell (1580–1626), to develop the sine law of refraction, which stated that when a ray of light passes from one transparent medium to another (such as air to water), the sine of the angle of the incident (original) ray divided by the sine of the angle of the refracted ray equals a constant. While this was a useful and demonstrable relationship, it led to a disagreement about the nature of light. Was it a motion through matter (that is, a wave)? Or was light made of particles? How did light travel? Could it travel in a vacuum? During the 1670s Huygens developed a wave theory of light in which he argued that the idea of a wave front represented the path of the light.

Newton criticized this wave theory, largely because it seemed to contradict the rectilinear nature of rays put forward by Kepler. Newton argued that light was corpuscular and proved it to his own satisfaction with a series of elegant experiments. By passing a beam of sunlight through a series of prisms, he demonstrated that white light was not pure light, as had been supposed, but rather was a composite of many colours (the spectrum). His demonstration has been called the *experimentum crusis* or crucial experiment, the demonstration that confirms the hypothesis. What Newton noticed was that light passing through a prism smeared into an oblong with colours at top and bottom. It had been assumed since antiquity that such an effect was the result of some corruption of the white light. If this was the case, it seemed reasonable to assume that by passing some coloured light through a second prism, the degree of corruption would be increased. So Newton passed light through a prism, then allowed a small amount of coloured light to project through a slit, and then through a second prism. There was no change in the colour of the light. In other words, nothing was added to or taken away (see figure 5.8.). To confirm this, he also placed two prisms together so that the first separated the light and the second, an inverted prism, gathered all the bands back together, producing a spot of white light.

Newton believed that light was composed of particles and that their differing speeds resulted in a differing angle of refraction when passed through a prism. If, for example, all red light was composed of small particles of similar nature, there seemed to be no mechanism to change the nature of the red particles as they passed through successive prisms.

This was hotly debated, the French following Descartes's and Huygen's lead in preferring a wave theory of light, but Newton's *Opticks* provided a foundation for a new English school of optical research throughout the eighteenth century.

Newton's *Opticks* also laid out a research program for natural philosophers who followed him. The book concluded with a series of "Queries," topics that interested Newton but which he had not had time to fully investigate. In addition, since there was a strong bias among Newton's peers against "theoretical" science, meaning the presentation of philosophical ideas without experimental demonstration, Newton presented his ideas as a series of questions. This list extended beyond optics, covering a range of scientific areas related to light such as the relationship between light and heat, the effect of the media of transmission on the behaviour of light, and the condition of the universe. For close to 100 years many natural philosophers and scientists interested in finding important areas of research started their inquiries



5.8 NEWTON'S DOUBLE PRISM EXPERIMENT

Sunlight passes through the prism "A" and falls on the screen. A portion of the spectrum produced (light of a single colour) passes through the screen at slit "*x*" and continues on to the second screen, where it goes through slit "*y*" and on to the second prism "B." The light is finally projected on to the wall. Newton's experiment demonstrated that light of a single colour could not be further broken up into a spectrum.

by taking on one of these questions. For example, in Query 18 (of the fourth edition of the *Opticks*), Newton noted that two thermometers, one in a vacuum and the other in a closed container of air, both seemed to heat up and cool down at about the same rate. This suggested to Newton that there must be a medium of propagation "more rare and subtle than the Air" that transmitted heat like a vibration. This observation prompted a number of scientists to look for the imponderable fluid or ether, an idea that was eventually resolved by the work of Einstein. It also got other scientists to investigate the nature of heat as separate from temperature, leading ultimately to the kinetic theory of heat and the laws of thermodynamics.

One of the most famous questions posed by Newton was Query 31 from the 1718 edition. Newton asked: "Have not the small Particles of Bodies certain Powers, Virtues, or Forces by which they act at a distance, not only upon the Rays of Light for reflecting, refracting, and inflecting them, but also upon one another for producing a great Part of the Phenomena of Nature?" Newton goes on to suggest that known forces such as gravity and electricity may play a role in the attraction of particles, but unknown forces may also be at work. By observing attraction, according to Newton, it should be possible to figure out the law of attraction that controls the way matter combines and functions. This idea contributed to the concept of chemical affinity, an idea used by most chemists to explain how matter combined. Affinity theory was one of the foundational concepts of modern chemistry until the nineteenth century when it was replaced by valence theory.

New Scientific Organizations

The new instruments, experiments, and the underlying assumptions about the relationship between humans and nature were fundamentally important to the creation of a new scientific enterprise in the seventeenth century. Equally important were the new institutional structures that developed in this period for the express purpose of fostering and supporting natural philosophy. The founding of such assemblies as the Royal Society of London and the Académie Royale des Sciences[3] in Paris contributed to a dramatic new organization of science, one that encouraged natural philosophers to develop social codes of behaviour, rules about who could do science and what counted as science, and statements about the secular usefulness of their enterprise. Just as Galileo had tried to separate religious and scientific claims to the monopoly of truth, so too did these new scientific societies. This was the beginning of the institutionalization of science, different in kind from the university-based science and distinct from the court-based science of the sixteenth century, although owing much to that earlier model. The breakdown of individual princely courts cast some natural philosophers adrift. Growing absolutism, especially in France, led to a more particular focus for patronage, as well as to a growing urban elite and intellectual culture in the capital cities. One hundred and fifty years of bloody religious wars caused people to look elsewhere than the church for salvational knowledge and for a secure group with status. The rising leisured class was looking for secular legitimation and something to do.

In about 1603 the first secular scientific society was formed, the Accademia dei Lincei (Academy of the Lynx) in Rome. This organization was founded by Federico Cesi (1585–1630), later Prince Cesi, and existed in great secrecy for the first years of its life, persecuted by the authorities including Cesi's father. Cesi was a man of huge intellectual energy and curiosity, who established a research program in natural history of great scope and imagination. When Galileo joined in 1611, the Accademia was given a major boost, especially since Galileo donated his microscope to it. After the condemnation of Copernicus, however, followed by Cesi's death in 1630 and Galileo's condemnation, the Accademia ceased to function. In 1657 a scientific society was founded in Florence, the Accademia del Cimento (of experiments). This society had neither a formal membership nor statutes and existed for ten years as a

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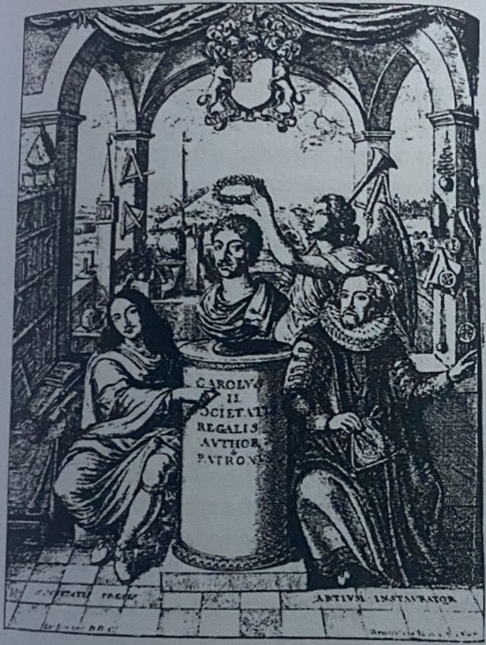
[3] The name of this organization changes according to informal or official use. Historians say "Académie des Sciences," although officially it is called "Académie Royale des Sciences." To make things more complicated, the name changed several times even though it remained the same group. Within the text, we will use the term commonly used by historians, that is, the Académie des Sciences.

Sprat was hardly a disinterested observer, it does seem that the Royal Society attempted to find a third way through the religious and civil disagreements of the period. While Royal Society members included those of many different religious affiliations (from Catholic to Puritan), what they had in common was the desire to keep clear of religious controversy and to do natural philosophy instead of theology.



5.9 FRONTISPIECE OF SPRAT'S *HISTORY OF THE ROYAL SOCIETY* (1667)

The Royal Society developed a strict method of choosing members, who had to be known to existing members and have an active interest in natural philosophy. The exception to this were some aristocrats, necessary to maintain the Society's elite nature. It also refused to allow women to join, although Margaret Cavendish, Duchess of Newcastle (1623–73), did attend some meetings and had published more books on natural philosophy than many of the members put together. They were also very hesitant to accept tradespeople, preferring instead the trustworthiness of gentry. The Royal Society developed a gate-keeping function, determining who counted in natural philosophical inquiry. Through the work of their first corresponding secretary, Henry Oldenburg (c. 1619–77) and through the publication of their journal, the *Philosophical Transactions of the Royal Society*, founded in 1665 and still published today, they also were able to determine what counted as proper natural philosophical work. Thus, in one fell swoop, the Royal Society became the arbiter of just who could be a natural philosopher and what qualified as acceptable natural philosophy.

The other successful seventeenth-century scientific society was established in a very different way. The Académie Royale des Sciences was founded in Paris in 1666 by Louis XIV's chief minister, Jean-Baptiste Colbert. Although there had been an informal network of correspondence centred on Father Marin Mersenne (1588–1648) since the 1630s, the Académie was a top-down organization, another element of the absolutist French state. Unlike the Royal Society, where members were elected and unpaid, the state appointed 16 academicians, paid as civil servants, to investigate the natural world as the king and his advisors required. So the Académie can be seen as the root of the professionalization of science, since this was the first instance where scholars were paid exclusively as scientists. Because their research agenda was set by the state, they could take on projects beyond the scope of individual scientists. For example, the Académie sponsored the measurement of one minute of arc of the Earth's surface, resulting in the first accurate measurement of the size of the Earth and the distance to the stars. In the long run, however, it was less successful than the Royal Society. An appointment as an Academician was often the reward for a life's work rather than an incentive to new work. Most of the massive projects came to nothing. Its journal, *Journal des Sçavans* (founded in 1665), was largely a reprint service. The Académie des Sciences did well as a promoter of science as an elite and respected activity, but it was not a place that sponsored innovation.

These new scientific societies created four enduring legacies for science as a profession. First, science was now seen as a public endeavour, although with carefully defined limits, members, and methods. Second, its cooperative nature was stressed, through projects such as the History of the Trades sponsored by the Royal Society and the History of Plants and Animals investigated by the Académie. Such undertakings led to the Enlightenment view that all was knowable if properly organized and to the sense of the utility of the knowledge gained. When Leibniz founded the Berlin Academy of Science in 1700, he chose as its motto *theoria cum praxi*, theory with practice.

Third, scientific communications were established as an essential element of the scientific enterprise. While it had been true that letters between natural philosophers (for example, between Galileo and Kepler) or within the letter-writing circle of Father Mersenne had been integral to maintaining a community of scholars, the establishment of scientific journals in the seventeenth century both broadened and controlled this community. These journals acted as a guarantor of veracity and reliability, even while issues were socially determined and highly contested. They also broadcast scientific ideas and experiments to a much larger audience, allowing ordinary people to take part in science by "virtual witnessing." This led to a wider interest in the investigation of nature and a greater acceptance of new scientific ideas and of scientists as respectable, if awe-inspiring people.

Finally, scientific societies established scientists as experts, qualified by membership to pose and judge questions about nature. This was especially true in

France, where election to the Académie was the culmination of one's life's work. But equally within the Royal Society, some natural philosophers, such as Newton or Boyle, were respected both within and outside the society as experts and significant scholars. Below them were the collectors, those who found interesting natural phenomena to report but who left theorizing to their betters, much as Bacon had laid out in Solomon's House. Thus, the seventeenth-century scientific societies established ideologies about science and its practice still with us today.

During the sixteenth century, connections between natural philosophers and skilled artisans aided greatly in the development of new ideas about nature and new problems to be investigated. This was also true during the seventeenth century, although the focus became the urban mercantile centre, rather than the princely court. Just as the scientists themselves were forming associations with their fellow scholars in these new, secular, non-court settings, often in major trading centres, they were also closer to shipyards, print shops, instrument makers, and chart makers. However, projects like the Royal Society's History of the Trades, an unmitigated disaster, shows us that the communication between these artisans and scholars was more complicated than one might think. The History of the Trades attempted to find out how all the different manufacturing trades in England were performed, so that natural philosophers might find a more rational scientific way to manufacture goods. Not surprisingly, the tradesmen were remarkably unforthcoming about their trade secrets, and the suggestions made by the bewigged gentlemen were at best unhelpful and at worst positively dangerous. It would take some time for a new collaborative approach to bring together the skills of craftspeople and the precision of scholars.

The Place of Women in the Study of Science

Most of this discussion of seventeenth-century science has focused on the contributions of men of science; this was, however, a period when women were attempting to make their mark on the study of the natural world. Both Anne Finch, Viscountess of Conway (1631–79), and Margaret Cavendish, Duchess of Newcastle, were interested in breaking into this previously clerical and male preserve. The same social and intellectual upheaval that made science a gentlemanly pursuit gave women a brief window of opportunity to become involved in natural philosophy. Bethsua Makin (c. 1612–c. 1674) wrote *An Essay to Revive the Ancient Education of Gentlewomen* (1673), arguing for the right and ability of women to study natural philosophy. Anne Conway corresponded with Leibniz and shared with him her theory of "monads" that became the basis of his particulate philosophy of the universe. Noblewomen such as Christina of Sweden engaged in natural philosophical conversations. Margaret Newcastle wrote many books of natural philosophy and attended a meeting of the Royal Society. She also composed what has been called the first English work of science fiction, *The Description of a New World, Called the Blazing World* (1666). These women, however, were exceptions. The seventeenth and eighteenth centuries saw restrictions on women's sphere in science as in much else.

Such restriction came from a general change in attitude to a gendered nature and from changing theories about women's role in society and in reproduction. In a pre-industrial society the vast majority of people existed in a close and symbiotic relationship with nature, which was perceived as female, a nurturing mother. The ideal was coexistence, not control. Mining, for example, was either the rape of the Earth or the delivery of a child, since minerals developed in the Earth's womb. Therefore, sacrifices, prayers, and apologies were necessary before mining could begin. The vitalism of Paracelsus, the natural magic of the neo-Platonists, and the naturalism of Aristotle all gave the female contribution of nature and to nature its due.

In early modern Europe, however, this began to change. As scholars began to view the Earth as exploitable, its image changed to a wild female who must be tamed. At the same time women were losing socio-economic status, becoming less autonomous and less able to earn wages or operate independently in craft guilds. Increasingly, accusations of witchcraft were levelled, especially against women. Scientific theories of sexuality and procreation changed. Where during the Middle Ages women had been recognized as providing something to initiate procreation (matter for Aristotle, female semen for medieval authors), during the sixteenth and seventeenth centuries theorists such as Harvey claimed that women were merely a receptacle, the incubator of offspring, and, as such, were totally passive. Likewise, women were no longer seen as equal partners in intercourse but rather seducers, enticing men into sexual activity that was deleterious to their health and intellectual well-being. Women were also losing their professional role in reproduction, as female midwives were replaced by licensed male surgeons or male midwives, who used their new technology of forceps to manage nature. Finally, with the introduction of the Mechanical Philosophy, introduced partly to deal with perceived disorder in the world, the soul of nature was stripped away, leaving only inanimate atoms; nature was dead, and women's claim to vitality through reproduction was rendered void. In other words, the natural philosophy of the seventeenth century articulated an ideology of exploitation, an image of the world that could be constructed according to man's specifications.

We can trace this change in attitude toward women as natural philosophers through the careers of two scientists: Maria Sybilla Merian (1647–1717) and Maria Winkelmann (1670–1720). Their careers demonstrate, on the one hand, the possibility of women's involvement in natural inquiry and, on the other, the restrictions to their participation through the creation of the new institutions of scientific societies.

Maria Merian's career illustrates the success a woman could have in a scientific field, particularly one based on an entrepreneurial model. Merian was born in Germany into a family of artists and engravers. From an early age she was interested in drawing and painting insects and plants. After marrying her stepfather's apprentice she became a renowned insect and plant illustrator, publishing well-received and beautifully engraved books. In 1699 the city of Amsterdam sponsored her travels to Suriname, where she observed and recorded many new plants and animals. On her return she created a bestselling book of these findings, which was published posthumously. Merian's career thus followed a very successful path in the older apprenticeship and mercantile model. However, after her death her work came to the attention of the new community of natural historians and philosophers, and her reputation suffered. Her Suriname book was strongly critiqued, condemned for her classification system and more particularly for her credence of slave knowledge about the use of these plants and insects. Her reputation, therefore, was greatly diminished in the increasingly misogynistic and racist attitudes of the eighteenth-century scientific community.

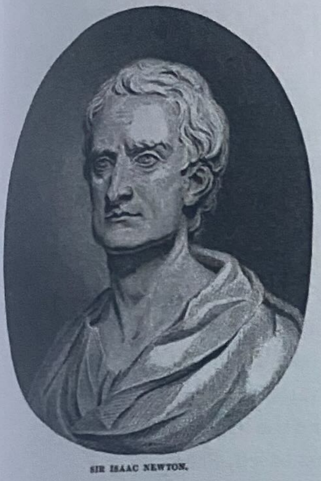
Maria Winkelmann was the daughter of and later wife of astronomers (she married Gottfried Kirch in 1692) and worked with both her father and husband on telescopic observations in Berlin. In 1702 Winkelmann independently discovered a comet and published her findings. She was a full participant in her chosen scientific field, but after Kirch's death in 1710 her status fell sharply. The Royal Academy of Sciences in Berlin refused to allow her to continue in her husband's position as official astronomer to the Academy, eventually appointing her less capable son instead. Even Leibniz's support was insufficient to help her maintain her position; the Academy was unwilling to set a precedent by allowing a woman to hold such an important job. In this they followed the lead of the Royal Society, which had likewise debated allowing Margaret Cavendish to join and had resisted the undesirable precedent. Eventually the Academy, embarrassed by her presence at the observatory, forced her to leave the premises; without access to large telescopes, she was unable to continue her observational work. The new organization of science, the Academy, proved itself to be more restrictive for women than the earlier apprenticeship model had been.

Seventeenth-Century Scientific Ideology

The new ideology of exploitation of and superiority toward nature reflected a changing attitude toward knowledge and nature. As crucial as the new knowledge and methodologies proved to be, of even greater significance in the creation of modern science were the new locales of scientific discussion and the new ideology and code of conduct the seventeenth-century societies established. Science had previously been the property of clerics and academics, but the upheaval of the seventeenth century—its religious and political wars, its economic strife—created an opportunity for a new group of gentlemen practitioners to develop a new standard for scientific conduct and a new place to practise science. This was particularly true in England, where the move away from absolutism at the end of the century allowed a certain freedom of association among the leisured classes and where the controversies associated with the Civil War and its aftermath gave gentlemen a desire for civility and an alternate way to establish matters of fact.

Robert Boyle was particularly instrumental in this transformation of scientific ideology. First, he set up laboratories, spaces for scientific experiment and investigation, in private locations, particularly in his sister's townhouse in fashionable Pall Mall in London. The privacy of this space was paramount, since Boyle was able to control access and behaviour within the site. That is, he could allow in people with the proper credentials, worthy to witness his experiments and guaranteed to know the proper way to behave. Similarly, private museums of natural history developed in this period all over Europe as private spaces, also belonging to aristocrats and gentry, who controlled visitors and bestowed on those visitors status through their permission to observe.

Because this space was private, Boyle could decide who had the proper credentials to observe, to take part in experiments, and to participate in the making of natural knowledge. He developed a number of criteria, later used by the Royal Society and other scientific bodies. The person seeking entry had to be known to Boyle or his circle and, thus, was a gentleman. This person should also be a knowledgeable observer, one who was able to validate the experimental knowledge and to witness matters of fact, rather than just gawk. Still, it was more important that the observer be of the leisured classes than that he or she be philosophically knowledgeable. This was clear from von Guericke's famous hemisphere experiment, which gained its status as one that created natural knowledge about the weight of the air by the presence of a large group of gentry onlookers (as can be seen in figure 5.5). Similarly, one of the important roles of the


SIR ISAAC NEWTON.

5.10 NEWTON

Engraving of Newton. From Sarah K. Bolton, *Famous Men of Science*. NY: Thomas Y. Crowell & Co., 1889.

Royal Society was to provide a credible audience for various experimental demonstrations, thereby establishing their veracity.

Because these experiments and demonstrations of knowledge were performed in spaces created and used by gentlemen, gentlemanly codes of behaviour were adopted as the codes of behaviour for scientists. For example, gentlemen argued for the openness and accessibility of private space at the same time that they were carefully controlling access to such places. Likewise, scientific laboratories as they developed claimed to be open public space while limiting access to those with the knowledge and credentials to be there. Gentlemen were very concerned with issues of honour and argued that their word was their bond. A gentleman never lied, which was why there was much outrage (and duels fought) at any suggestion of cheating. This was why matters of fact could be established through the witnessing of a few gentlemen, who would, of course, see the truth of the investigation and report it accurately to others. A scientist's word was also his bond. Scientists would not cheat or lie, and thus they claimed the role of a completely trustworthy enclave in society. The Royal Society in concert with Boyle created a community of scientists who could decide what constituted truth and reality and who were allowed to make pronouncements on that reality.

Conclusion

By the time Newton died in 1727, the place of the natural philosopher had changed considerably. The image of the natural philosopher had shifted even further away from the "pure" intellectuals of ancient Greece, the Islamic wise men, or even the courtiers of Galileo and Kepler's era. A bust commemorating Newton sits in the entrance hall of Trinity College, Cambridge. (See figure 5.10.) It does not present him as an erudite scholar or as an important member of society, as had earlier portraits from his student days, or as Master of the Mint. Rather, it presents him as a modern Caesar who, with firm gaze and noble brow, has conquered all he surveyed. While Caesar captured Rome and gained an empire, Newton conquered

Nature and made it man's dominion. The poet Alexander Pope said of Newton's life: "Nature and Nature's Laws lay hid in night / God said, 'Let Newton be,' and all was light."[4]

By the end of the seventeenth century many aspects of modern science had been established. Philosophers of this period of scientific revolution had wrestled with questions of epistemology at the beginning of the century and decided on a behavioural model of truth-telling by the end. Some of these thinkers developed new ideas, theories, and experimental discoveries, setting in place a series of research programs for the coming century. They had also introduced a new methodology of science, which included the mathematization of nature and a new confidence in, and reliance on, experimentation. New secular scientific institutions sprang up; with them came an articulation of the utility of their knowledge to the state and the economy. Finally, the domination of natural philosophical enquiry by secular gentlemen from the leisured classes ensured a code of behaviour that was gendered and class-based. These ingredients led to a new scientific culture that rapidly assumed a recognizably modern face. All these changes together constituted a scientific revolution.

Essay Questions

1. Was there a scientific revolution? If so, of what did it consist?

2. In what way can Newton be seen to have completed the Copernican revolution in astronomy?

3. In what ways were the Royal Society and the Académie des Sciences similar and different?

4. What role did women play in the development of natural philosophy and did this change over time? Why or why not?

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[4] Alexander Pope, "Epitaph Intended for Sir Isaac Newton." In Westminster Abbey, 1735.